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DETERMINING THE VELOCITY OF AN AVERAGE-SIZE CONDENSATE DROP IN A FLOW OF SATURATED VAPOR

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Theoretical considerations on determining the velocity of condensate drops in a flow of saturated vapor are given, based on the example of the efficiency of a turbine stage operating in the wet-steam range. Equations of motion for a condensate drop, derived by various authors, are compared, showing a large discrepancy in the values obtained at a pressure of 1.033 atm and a temperature of 100°C. Special experimental work is recommended.

author

Current Russian and non-Russian literature is paying considerable attention to investigations on turbine stages operating in the wet-steam region. This new emphasis is due to the vague quality of existing suggestions for determining the energy loss produced by the presence of moisture in the steam flow.

One of the basic questions in the problem of determining the efficiency drop of a turbine stage operating in the wet-steam regime is that of finding a relationship between the velocity of condensate drops entrained by the flow and the velocity and parameters of the steam itself.

To find this relationship it is customary to employ the formula for resistance of a body moving in a vapor flow (Bibl.1, 2) where the drop form is taken to be spherical:

$$P = \frac{G}{g}\,\frac{dC_w}{dt} = \psi F \gamma_s \frac{C_{rel}^2}{2g}, \tag{1}$$

where $\psi = f(Re)$ is the coefficient of lateral resistance of the sphere; F is the median cross-sectional area of a drop of average size; γ_s is the specific weight of the steam; $C_{rel} = C_s - C_w$ is the relative velocity of motion of a drop in the steam; $g = 9.81$ m/sec^2; G is the weight of an average-size drop.

If we use the well-known approximate relationship for a smooth sphere

$$\psi = 0.4 + \frac{40}{Re} = 0.4 + 40\,\frac{\mu_s g}{C_{rel} d_0 \gamma_s}$$

and substitute it and the values of G, F, and $dt = dS/C_w$ in eq.(1), then after

* Numbers in the margin indicate pagination in the original foreign text.

simple transformations we obtain the differential equation

$$dS = \frac{10}{3} d_0 \frac{\gamma_w}{\gamma_s} \frac{C_w dC_w}{C_{rel}^2 - \frac{100 \mu_s g}{d_0 \gamma_s} C_{rel}}, \tag{2}$$

where S is the path of the drop in the steam, in m; d_0 is the diameter of the average-size drop, in m^2; γ_w is the specific gravity of water, in kg/m^3; μ_s is the dynamic coefficient of viscosity of the steam, in $kg \cdot sec/m^2$.

Equation (2) is usually solved under the assumption that the diameter of a drop is constant after it has been formed during the break-up of a film of water, i.e., we take the size of the drop to be independent of the relative /57 velocity of motion. However, an examination of the picture of the motion of a jet of drops in a gas flow (Bibl.3, 4) permits a conclusion as to the possibility of a change, while in transit, in the magnitude of an average-size drop due to merging or settling of smaller drops on larger ones. It is therefore interesting to make a comparison of the solutions of eq.(2) based on the propositions of constancy and of variation in drop diameter during the process of acceleration.

As a typical example of a solution assuming constancy of the drop diameter it is possible to use the solution given by Freudenreich (Bibl.1). This solution, after certain conversions, is obtained in the form

$$C_w = 2C_s - \frac{(kS + 4\sqrt{C_s})^2}{8} + \sqrt{\left[2C_s - \frac{(kS + 4\sqrt{C_s})^2}{8}\right]^2 + \frac{C_s(kS + 4\sqrt{C_s})^2}{4}}, \tag{3}$$

where
$$k = \frac{8\gamma_s \sqrt{\nu_s}}{\gamma_w (d_{max})^{3/2}};$$

Here, ν_s is the kinematic viscosity coefficient of the steam, in m^2/sec.

Freudenreich obtained a formula for the velocity of a drop having the greatest diameter in an atomized jet. Other reports (Bibl.4, 5) indicate that $d_0 \cong d_{max}/2$. To determine the velocity of an average-size drop, the quantity k in eq.(3) must be substituted in the form of

$$k_0 = \sqrt{8} \frac{\gamma_s}{\gamma_w} \frac{\sqrt{\nu_s}}{d_0^{3/2}}.$$

In addition to the exact formula (3), Freudenreich proposed the approximate formula

$$F(\varepsilon) = \frac{2 - \varepsilon}{\sqrt{1 - \varepsilon}} - 2 \cong \frac{\varepsilon^2}{4}, \tag{4}$$

where $\epsilon = C_w/C_s$, obtained by expansion of the function $F(\epsilon)$ in a series, utilizing the first three terms of the expansion. The author demonstrated the suitability of eq.(4) only for small values of ϵ.

Later, Dekhtyarev (Bibl.6) transformed eq.(4) and presented it in the form of

$$\epsilon = 2.42 \frac{\mu_s \gamma_s}{\sigma_w} C_s^2 \sqrt{\frac{S}{\sigma_w \gamma_w}}. \tag{5}$$

The limits of applicability of eq.(5) were demonstrated by Dekhtyarev for $\epsilon = 0.2 - 0.3$. However, he took the S in eq.(5) to mean the value of the axial clearance rather than the path traversed by a drop. This resulted in a decrease in the quantity ϵ by a factor of $\sqrt{\sin\alpha}$ (α being the angle at which the steam emerges from the nozzle) as against the value of ϵ derived by Freudenreich.

In addition to the Freudenreich solution, the relationship between the drop velocity, the path traveled, and the steam velocity can be found by integration of eq.(2), keeping d_0 and C_s constant:

$$\int_0^S dS = \int_0^{C_w} A \frac{C_w dC_w}{C_{rel}^2 - BC_{rel}},$$

where A and B are constants, yielding /58

$$A = \frac{10}{3} d_0 \frac{\gamma_w}{\gamma_s}, \qquad B = 100 \frac{\mu_s g}{d_0 \gamma_s}.$$

After transformations, the solution was obtained in the form of

$$S = \exp\left(\frac{C_{rel} + B}{C_s + B}\right)^A \left[\frac{(C_{rel} + B) C_s}{(C_s + B) C_{rel}}\right]^{\frac{AC_s}{B}}. \tag{6}$$

To obtain solutions that take account of variations in the diameter of the drop during its transit, it is necessary to find the relationship between the diameter of the average-size drop and the relative velocity of motion and the physical properties of the moving medium and the drop.

In an earlier report (Bibl.2), eq.(2) was solved on the basis of the expression for d_0 obtained from the break-up criterion. This solution then takes the form

$$S = k_1 \left[\frac{C_s}{3C_{rel}^3} - \frac{1 + BC_s}{2C_{rel}^2} + \frac{B_1(1 + B_1 C_s)}{C_{rel}} - B_1^2 (1 + B_1 C_s) \times\right.$$

$$\times \ln \frac{1+B_1C_{rel}}{C_{rel}} + \frac{1}{6C_s^2} - \frac{B_1}{2C_s} - B_1^2 + B_1^2(1+B_1C_s) \times$$

$$\times \ln \frac{1+B_1C_s}{C_s} \Bigg], \tag{7}$$

where

$$k_1 = 24\,\sigma_w g\,\frac{\gamma_w}{\gamma_s^2}; \qquad B_1 = \frac{13.9}{\sigma_w}\mu_s.$$

A simpler formula for C_w can be obtained by solving eq.(2), substituting in it the value of d_0 according to the well-known empirical formula by Nukiyama and Tanazawa, making use of its first term. The possibility of such an operation is shown elsewhere (Bibl.7). The solution is obtained in the form

$$C_w = C_s + \frac{P_1}{2(S-P_1/2C_s)} - \frac{\sqrt{4P_1^2 + 8(S-P_1/2C_s)P_1C_s}}{4(S-P_1/2C_s)}, \tag{8}$$

where

$$P_1 = \frac{10}{3}\,\frac{\gamma_w}{\gamma_s}\,\frac{E}{10^6(1+100\,\mu_s g/E\,\gamma_s)}; \quad E = \frac{585}{10^6}\sqrt{\frac{\sigma_w}{\rho_w}};$$

Here, σ_w is the coefficient of surface tension of the water, in dyne/cm; ρ_w is the density of water, in gm/cm^3.

On the basis of eqs.(3) and (5) - (8), comparative calculations were made for the case of the flow of saturated steam with the parameters P = 1.033 atm, **t = 100°C in the axial clearance of the turbine stage. The results of the calculations are shown in Figs.1 and 2.**

A comparison of the calculation results with respect to the curves of $\epsilon = f(C_s)$ (Fig.1) for the range of velocities reviewed, demonstrates the applicability of Freudenreich's approximation function for $\epsilon \leq 0.35$, i.e., up to $C_s \cong 175$ m/sec. At greater velocities, the discrepancy in the results is considerable since the curves 1 and 3 have curvatures with differing signs. For velocities above 280 m/sec, eq.(5)loses any physical meaning since the drop is accelerated to velocities greater than the steam velocity. This statement also holds true for the Dekhtyarev formula (curve 4) up to steam velocities greater than 408 m/sec. Calculations on the basis of eq.(5) were performed by substituting for S, in accordance with Dekhtyarev, the values of the corresponding axial clearance for the angle $\alpha = 13°25'$. The curve of $\epsilon = f(C_s)$ according to eq.(6) has a steeper slope than the curve obtained from eq.(3) where, at an increase in the steam velocity up to 400m/sec,the values of ϵ derived from the two formulas differ by a factor of 2. Curves 6 and 7, obtained as a result of calculations according to eqs.(7) and (8), also exhibit a relatively steep slope and pass below the curve obtained from eq.(6). The maximum difference in the values of ϵ, calculated according to eq.(6) and according to eq.(7) respectively, is not more than 12%. /59 /60

The curves for the velocity values in relation to the path covered (Fig.2) are less graphic. However, they offer a possibility to estimate the character

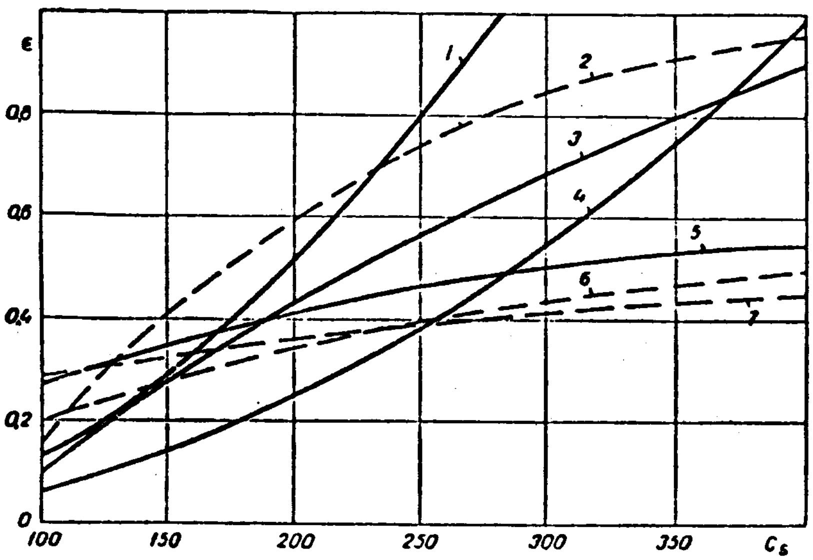

Fig.1 Effect of Steam Velocity (m/sec) on C_w/C_s = ε at S = 12.95 mm
1 - Accd. to Freudenreich; 2 - Accd. to eq.(3) for d_0; 3 - Accd. to eq.(3) for d_{max}; 4 - Accd. to Dekhtyarev; 5 - Accd. to eq.(6); 6 - Accd. to eq.(7); 7 - Accd. to eq.(8).

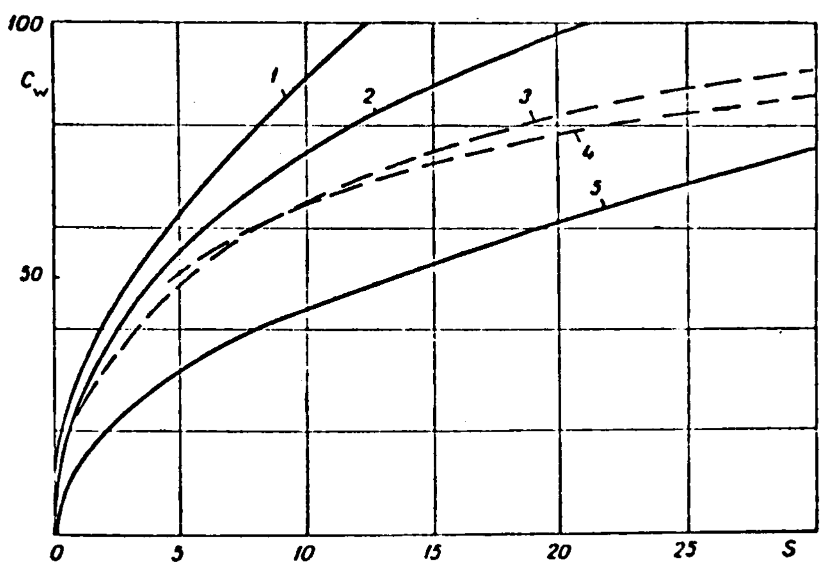

Fig.2 Effect of Path (mm) on Drop Velocity for C_s = = 200 m/sec
1 - Accd. to Freudenreich; 2 - Accd. to eq.(6); 3 - Accd. to eq.(8); 4 - Accd. to eq.(7); 5 - Accd. to Dekhtyarev

of acceleration of an average-size drop along a definite segment of the path.

This comparison of the results of calculations by the various formulas demonstrates a large discrepancy in the values obtained for the velocity of an average-size drop, at P = 1.033 atm and t = 100° C. To clarify the true values of drop velocities it is necessary to perform special experimental work. At present, there is no reference in the published literature to such experiments for the range of velocities reviewed here. Obviously, without experiments of this type it is impossible to determine the magnitude of the drop velocity in the steam flow with any degree of assurance as to its authenticity.

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